LASER DIAGNOSTIC ANALYSIS OF NO FORMATION IN A DIRECT INJECTION DIESEL ENGINE WITH PUMP-LINE-NOZZLE AND COMMON RAIL INJECTION SYSTEMS

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Laser-induced fluorescence (LIF) imaging was applied to investigate NO formation in a directly injected diesel engine with realistic combustion chamber geometry. The technique, which uses KrF excimer laser excitation, was previously successfully applied in gasoline engines. Influences of interfering species depending on the spectral range used for LIF detection was investigated by spectrally resolved LIF detection. Laser and signal attenuation were assessed in separate experiments using spectrally resolved O_2–LIF detection with the same optical path as in the imaging measurements. The in-cylinder NO concentration was compared for different injection systems and operating conditions.

Introduction

Future stringent legislation on NO_x emissions is a major challenge for manufacturers of engines for automotive applications. In diesel engines, overall air/fuel ratios deviate significantly from unity, which makes the use of efficient exhaust gas after treatment systems difficult. Therefore, further decreasing NO_x net emissions requires reducing the amount of NO formed during the combustion process itself. The development of new low-emission internal combustion (IC) engines, however, would be greatly facilitated by improving the knowledge of the basic physical and chemical processes responsible for pollutant formation using laser-based imaging techniques.

Different attempts of laser-based imaging measurements in diesel engines have been shown previously. Typical drawbacks were related to strong light attenuation (both laser and signal light) and intense laser-induced fluorescence (LIF) interference from combustion intermediates and hot oxygen. Ter Meulen et al. [1] used 193 nm laser excitation (NO D-X(0,1) band) which is strongly attenuated within the combustion chamber. They applied a technique to correct for laser intensity variations within the combustion chamber, assuming homogeneous distribution of absorbing and scattering species. Dec et al. [2], on the other hand, used 226 nm radiation generated by an optical parametric oscillation (OPO) system to excite the NO A-X(0,0) transition. By using partially oxygenated fuels (non-sooting fuels), they reported measurements without significant laser attenuation. In previous studies in gasoline IC engines

[3,4] and high-pressure flames [5], however, comparisons have shown that excitation at 248 nm (NO A-X(0,2) band) is favorable for IC engine applications. Here, the laser attenuation is minimized, and the possibility of detecting NO–LIF shifted toward shorter wavelengths (emission from the [0,1] vibrational band at 237 nm) strongly discriminates NO–LIF against contribution of interfering LIF caused by hot molecular oxygen [6] and intermediate hydrocarbons [7]. However, with detection at 237 nm, signal attenuation has to be kept in mind, and a technique of correcting for this effect using the Franck–Condon pattern of excited O_2 has been described and previously applied to spark-ignition engine experiments [8].

Experimental

The engine used in this work is based on the DaimlerChrysler BR500 engine series (Table 1). This optical engine [9] preserves all details of the combustion chamber design due to an original cylinder head and an quartz piston window into which the original contour is machined. This arrangement allowed full and almost undistorted optical access and also to the squish area. Since soot can rapidly foul the windows, an arrangement as presented by Espey et al. [10] was used which enabled easy access for window cleaning. To avoid window fouling due to the lubricating oil, self-lubricating piston rings were used such that the upper liner runs without oil. The engine is designed to run at all load conditions up to an engine speed of 1500 rpm controlled by a

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TABLE 1
Engine data

Engine base type	DaimlerChrysler BR500
Cycle	Four stroke
Number of intake valves	2
Number of exhaust valves	2
Bore	130 mm
Stroke	150 mm
Compression ratio	17.25:1
Displacement	2.0 l

dynamometer. Full load conditions with peak pressures up to 200 bar can be investigated. A pressurized air supply in combination with an heat exchanger was used to provide intake air conditions similar to the turbo-charged series 500 multicylinder engine without significant swirl in the combustion chamber. The engine can be operated with two injection systems: the pump-line-nozzle (PLN) system, which consists of a cam-driven pump, a short injection line, and an injection nozzle, or the common rail (CR) system, in which a constant rail pressure is provided [9]. With PLN, the injection pressure increases from a low level after start of injection. This pressure history produces a triangular shape of the injection rate. With CR, the rail pressure is acting all the time. Therefore, the rate of injection is approximately rectangular. The ignition started at 3° before TDC with injection duration of 1.25, 0.99, and 0.70 ms at CR pressures of 600, 800, and 1200 bar, respectively, and 0.91 ms with the PLN system. In all cases, the engine was operated at 25% load.

The light from a tunable KrF excimer laser (Lambda Physik LPX 150) was formed to a horizontal light sheet and aligned through the windows in the cylinder head. The position and size of the observed plane is depicted in Fig. 1. Around top dead center (TDC) (± 20 °CA [degree crank angle]) the beam path is blocked by the piston. Two different setups were used for the measurements (Fig. 2). With the laser tuned to the NO A-X(0,2) O_{12} bandhead (247.94 nm), planar NO–LIF images were taken using an intensified charge-coupled device (ICCD) camera (Princeton Instruments ICCD-576 GIRB) equipped with appropriate bandpass filters to selectively detect NO A-X(0,1) emission with efficient suppression of elastically scattered light (combination of 240 nm short-pass filters and an array of four mirrors with high reflectivity at 230–240 nm at 45°). With the same setup, background interferences were assessed with the laser tuned to an off-resonant position (248.07 nm). For a preliminary calibration of signal intensities, a McKenna flame (methane/air flame at $\phi = 0.9$ doped with different NO concentrations of 300–1400 ppm) was installed next to the dismounted cylinder head. Signals were observed via a coated aluminum mirror through the piston window using the set of filters as described above. Both laser sheet optics and detection pathlength were kept to the in-cylinder imaging setup as close as possible.

By replacing the bandpass filters by an imaging spectrograph (Acton Research, SpectraPro-275 with 600 grooves/mm grating), fluorescence emission spectra were acquired for assessing LIF interferences in the engine running under different operation conditions. A similar setup (Acton Research SpectraPro-150, 300 grooves/mm grating) was used for measuring light attenuation using O_2–LIF after tuning the laser to 248.5 nm for exciting the P(9) rotational transition within the O_2 B-X (2,7) band. To increase signal-to-noise ratios, spectra were averaged over subsequent engine cycles. Therefore, a
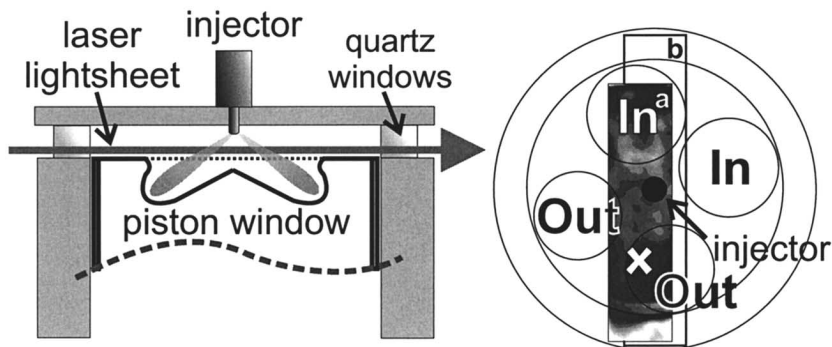

FIG. 1. Left, Position of the light-sheet within the combustion chamber and geometry of the ω-shaped piston window. Right, Position of the imaged area inside the diesel engine. The x within the field of view of the imaging measurements marks the position of the spectroscopic measurements (Fig. 4), the absorption measurements (Fig. 6), and the calibration. Measured field as presented in Fig. 5 (21 × 92 mm) (a). Field of view of the measurements in Fig. 7 (18 × 111 mm) (b).
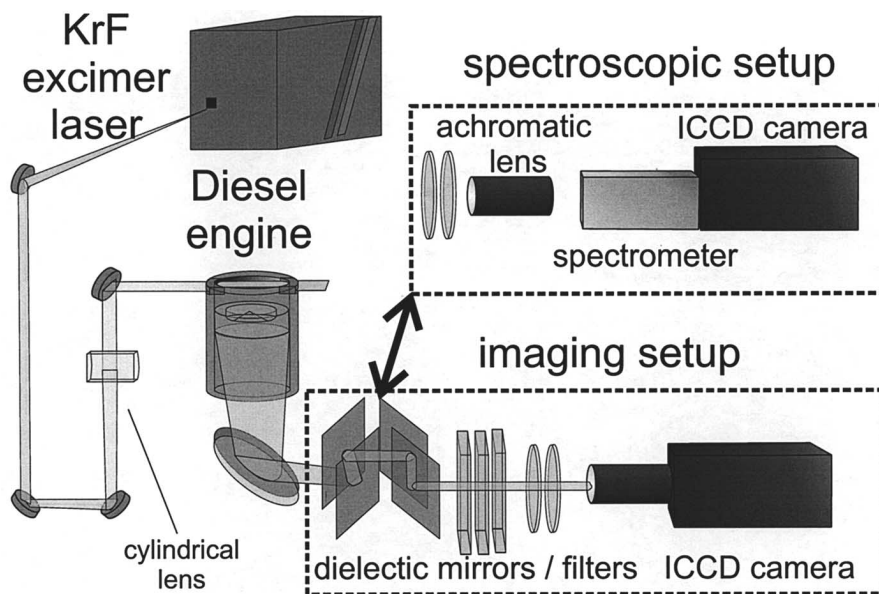
FIG. 2. Schematic picture of the diesel engine and the optical setups for planar LIF imaging and spectroscopic investigations.
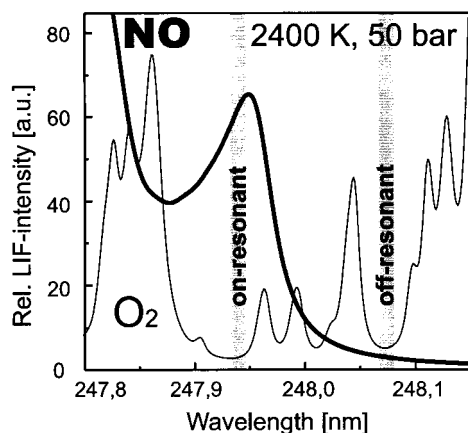

FIG. 3. Spectral simulation for NO and O_2–LIF (assuming detection band pass of 230–240 nm) for 50 bar and 2400 K. The on- and off-resonant excitation wavelengths used in the study are shown.

measuring position within the ω-bowl was chosen, where window fouling due to soot deposition was minimized even after extended engine operation.

Results

Interfering signals were assessed comparing fluorescence emission spectra upon excitation on the NO A-X O_{12} band head (at 247.94 nm) and at a spectral position where NO is not excited effectively (at 248.07 nm). Those wavelengths were chosen using spectra simulations (Fig. 3) to ensure that the O_2–LIF contribution is of the same magnitude with both excitation wavelengths. Laser-induced emission spectra from the running engine are shown in Fig. 4. In these measurements, the intake air was enriched to 28% oxygen to extend the measurement period before the window transmission was significantly reduced by soot deposition. The emission spectra at 20 °CA after top dead center (ATDC) (actual pressure, 53 bar) show a strong contribution of O_2–LIF. Due to the Franck–Condon pattern, the emission mainly appears in the red-shifted range at wavelengths above 255 nm. Besides the apparent band structure, a strong broadband fluorescence contribution covers the whole investigated wavelength range above 260 nm, which is attributed to intermediate combustion products like polycyclic aromatic hydrocarbons and partially oxidized hydrocarbons. Therefore, in this spectral region, NO detection would be strongly affected by background signal. The NO A-X(0,1) emission band at 237 nm, on the other hand, is not affected by interfering LIF signals, enabling selective NO detection. Late in the cycle due to decreased pressure, the relative intensity of O_2–LIF is much reduced, whereas the broadband background at longer wavelengths persists. Therefore, for imaging measurements in the diesel engine reported here, detection of the blue-shifted NO emission was preferred.
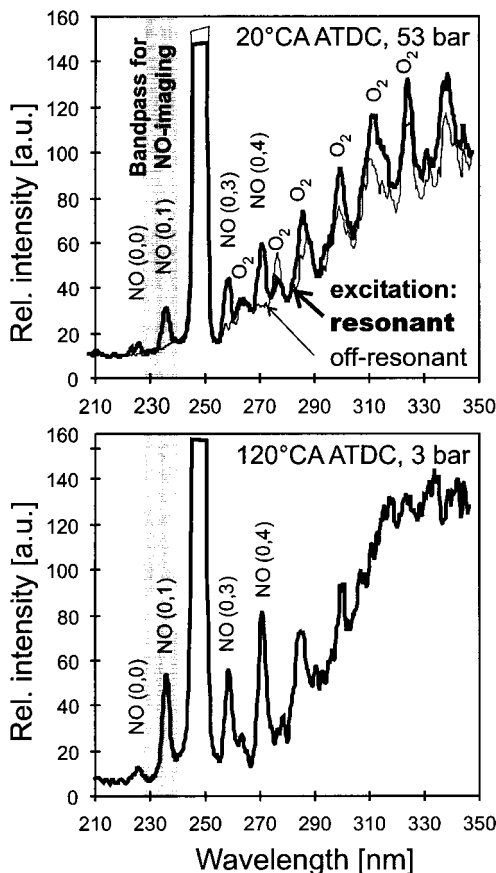
FIG. 4. Emission spectra obtained after on- and off-resonant excitation (see Fig. 3). Top, Detection at 20 °CA ATDC. Due to high pressures, strong contribution of O_2–LIF can be seen in the spectral range above 260 nm. Additional broadband fluorescence which persists throughout the engine cycle is present in the same range (bottom, 120 °CA ATDC). The spectra shown are averaged over 70 cycles and are acquired at the position marked with x in Fig. 1.

FIG. 5. Top, Single-shot NO–LIF images in the diesel engine (25 °CA ATDC, standard diesel fuel, 28% oxygen, actual pressure $p = 43$ bar) with on- and off-resonant excitation. Bottom, The graph shows typical profiles through the central area of the cylinder for on- and off-resonant excitation (see Fig. 3).

Single-shot images detected through the set of dielectric filters clearly show that the background contribution of interfering species is small (<10%) with the detection scheme chosen. In Fig. 5 typical single-shot images are compared (detection 20 °CA ATDC) with on- and off-resonant excitation. Whereas the off-resonant images show weak signals, in the resonant images isolated areas of NO–LIF signal are found in the middle of the combustion chamber. Since the measured plane is situated above the major part of the spray cones, in the middle of the combustion chamber NO is only found if gas pockets are moved upward by turbulent transport. At the same time, reproducibly high NO concentrations are found within the squish area where the
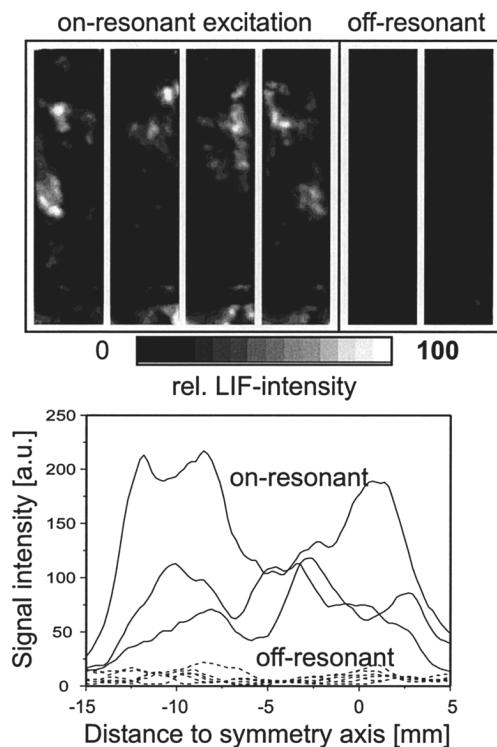
flame is burning after it has left the piston bowl. Furthermore, the single-shot images shown in Fig. 5 are not corrected for signal attenuation. Therefore, the NO–LIF signal in the squish area (lower part of the frames) appears even more intense due to reduced optical path length within the combustion chamber.

Due to the geometry of the engine, signal light from different parts of the observed plane travels different distances through the postflame gases. Signal attenuation is assessed by spectrally resolved O_2–LIF detection using the identical geometry as in NO–LIF measurements. Hot oxygen can easily be excited within the tuning range of a KrF excimer laser. When exciting transitions in the B-X(2,7) band, a number of emission bands shifted to both shorter and longer wavelengths can be monitored. Deviations in relative signal intensities from the well-known Franck–Condon pattern can then be attributed to a wavelength-dependent signal attenuation. The short wavelength region can be investigated using blue-shifted O_2-emission lines from transitions
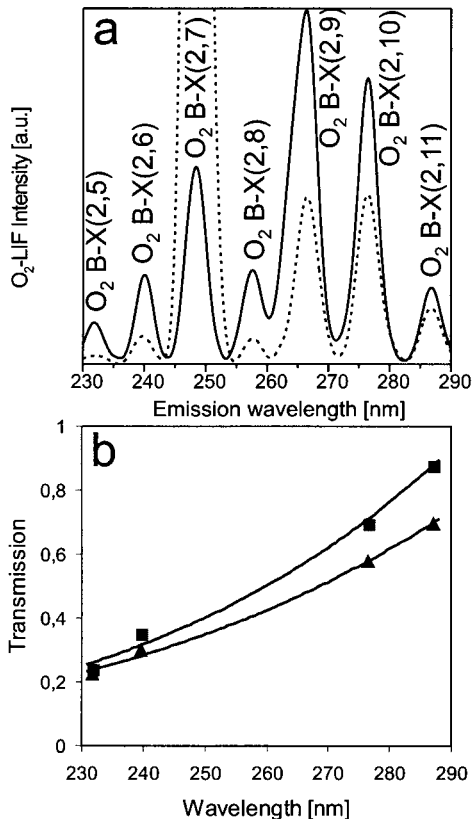
FIG. 6. Measurements of signal attenuation using O_2–LIF at the position marked with x in Fig. 1. The optical pathlength between the observed plane and detection window is 40 mm. (a) O_2–LIF emission spectra measured in the diesel engine compared with measurements in a lean atmospheric pressure flame (see text). (b) Resulting signal transmission properties using commercial diesel fuel. Oxygen concentration: 28% (rectangles) and 24% (triangles).

in the (2,6) and (2,5) vibrational bands around 239 and 231 nm, respectively, which are representative for attenuation of the detected NO–LIF at around 237 nm. Measured LIF intensities depend on the local oxygen concentration, temperature, and signal absorption. By referencing the measured signal in the short wavelength range to emissions in the redshifted spectral range, temperature and concentration effects cancel. Therefore, the O_2–LIF intensity of each emission band is normalized to the measured intensity at 402 nm [(2,19) band] where light attenuation in the combustion chamber is assumed to be negligible. Since absorption cross-sections were found to be strongly wavelength dependent, the major contribution is not due to attenuation by soot. Therefore, its contribution to signal attenuation at 402 nm is neglected in this attempt. Fig. 6 shows the

comparison of the O_2–LIF emission spectra from an atmospheric pressure flame and in-cylinder measurements in the diesel engine fueled with commercial diesel fuel. A central position within the piston as marked in Fig. 1 was investigated at 40 °CA ATDC with an actual pressure of 23 bar. Both spectra are normalized at an O_2–LIF emission at 402 nm. The signal attenuation observed at different O_2 emission bands between 230 and 260 nm is shown in the lower frame. At the detection time, investigated here, the light path between the illuminated plane and the detection window is 40 mm within the combustion chamber, resulting in small transmissions in the range of 25% to 35% at 235 nm.

Full quantification of NO–LIF signal intensities in an inhomogeneous combustion environment like direct injection (DI) diesel combustion requires further information on local temperature and gas composition. The uncertainties in NO calibration if these parameters are unknown are discussed in Ref. [4]. The variation of NO–LIF signal intensity with temperature, however, leads to an increase of approximately 20% per 200 K above 2000 K. The variation of NO–LIF signal intensities found at different operation conditions and different detection timings is much larger and therefore significant even without detailed knowledge about local temperatures. Calibration of signal intensities by doping NO to the fresh gases used in homogeneous gasoline engine combustion [11] is not feasible here since local variations in fuel concentration lead to unpredictable levels of NO reburn. On the other hand, adding NO to the motored engine provides only insufficient signal intensities due to negligible population of the probed vibrational level. Therefore, to estimate the level of in-cylinder NO concentrations, an NO-doped lean McKenna burner flame was used as an external calibration source. Different amounts of NO (five different concentrations between 300 and 1400 ppm, laser power density below 7.5 MW/cm^2) were doped to the fresh gases, and the related increase in NO–LIF intensity was used for comparison with NO–LIF intensities obtained in the in-cylinder measurements. When transferring the calibration from the atmospheric pressure system to in-cylinder measurements, pressure-dependent effects on line broadening and shifting were included [5,12,13]. A rough calibration can be given for the point where the transmission properties of the burned gases have been assessed with the oxygen–LIF technique shown above. For the engine using the PLN injection system with commercial diesel fuel and oxygen enrichment to 24%, at 40 °CA ATDC NO number densities in the investigated area (position marked in Fig. 1) are in the range of 5×10^{16} molecules/cm^3 with an uncertainty of $\pm 50\%$.

In Fig. 7, the NO signal intensities (averaged over eight individual cycles) at 40 °CA ATDC are compared for different injection conditions. Two different types of injectors are used under normal operating conditions using commercial diesel fuel
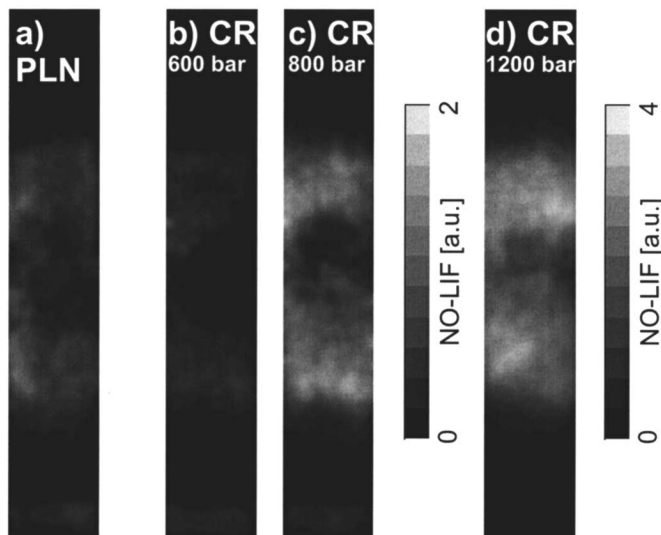
FIG. 7. Averaged NO–LIF distribution for different injection conditions. (a) PLN system. (b through d) CR injector with 600, 800, and 1200 bar injection pressure. Detection at 40 °CA ATDC with actual cylinder pressures of 21–22 bar. The images are corrected for distortion effects caused by the ω-shaped detection window. At outer parts of the field of view, signal intensities are reduced due to soot deposits within the piston bowl.

without oxygen enrichment in the intake air. In the PLN system, the fuel pressure is linearly increasing with injection time (starting from about 100 bar up to 1750 bar at full load). At 25% load, as shown here, an injection pressure of approximately 600 bar is reached. The CR system, on the other hand, provides fixed rail pressure of up to 1600 bar. Therefore, at 25% load the CR system yields much higher injection pressure, decreasing droplet sizes and increasing air entrainment. This minimizes soot formation but increases combustion temperatures and burn rates. This, in turn, causes a strong increase in NO formation and allows longer time for NO being formed within the hot environment. This behavior can be clearly seen from the images in Fig. 7. The images are corrected for image distortion. Signal attenuation is corrected for assuming homogeneous absorption cross-sections throughout the combustion chamber using the data obtained from the O_2–LIF measurements (Fig. 6). Due to the late detection, no significant correlation of the region where NO occurs and the position of the fuel jets was observed in the investigated plane. Lowest NO–LIF intensities were found in the PLN system. The NO–LIF signal intensity with the CR system at 1200 bar is higher by a factor of four. However, by decreasing the rail pressure (here to 800 and 600 bar), NO–LIF intensities are decreased. Under these conditions, the difference between the two injection systems is reduced.

Conclusions

For the first time, in-cylinder NO–LIF measurements in a realistic DI diesel engine using 248 nm excitation in the NO A-X(0,2) band are performed.

Spectroscopic measurements show that to minimize interference from oxygen and LIF of polycyclic aromatic hydrocarbons (PAHs) the NO signal is best detected around 237 nm, blue-shifted compared to the excitation wavelength. For assessing the level of signal attenuation in this range, additional measurements have been performed using the Franck–Condon pattern of the emission spectrum of excited oxygen.

At the earliest detection timing possible in the engine under study (20 °CA ATDC), it has been shown that NO can be detected selectively with a background contribution below 10%. Different operating conditions varying the injection system and injection pressures have been performed. It was shown that valuable information about the NO formation under these conditions was obtained from the two-dimensional NO–LIF measurements. First attempts of quantifying NO–LIF intensities are shown.

Outlook

With the present setup, the laser beam is blocked at TDC ± 20 °CA. Variations in the piston setup will provide access to the flame within the piston bowl. This will allow further insight in the NO formation in the developing spray flame.

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COMMENTS

Christian Eigenbrod, ZARM, University of Bremen, Germany. On one hand, focal depth of a lens operated in the low UV is very limited. On the other hand, the molded piston you use forms a complicated lens. How do you correct optical distortion, and how do you guarantee that the light-sheet is in the focal plane?

Author's Reply. The shape of the piston window is optimized in order to minimize image distortion at crank angle positions around TDC. For crank angle positions deviating from TDC, limited image distortion occurs, which is corrected by image processing. Defocusing of the imaged plane could not be observed for the investigated crank angles.

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William J. McLean, Sandia National Laboratories, USA. Previous LIF measurements of NO_x in diesel engines have required large corrections for fluorescence quenching to achieve quantitative results. Have you included such corrections in your analysis?

Author's Reply. When translating calibration information from the calibration flame to engine conditions, temperature- and pressure-dependent quenching rates are applied based on equilibrium gas compositions for the respective combustion environments. However, spatial inhomogeneities in gas composition within the combustion chamber cannot be accounted for so far. The influence of these inhomogeneities on NO quantification in direct-injected engines is reviewed in Ref. [4] (in this paper). Based on equilibrium gas compositions for an air/fuel ratio between 0.5 and 3, quenching rates vary about 20%.